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A Novel Method for Estimating Wind Turbines Power Output Based On Least Square Approximation

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Abstract*— *According to modernization in all over the world, renewable energies are getting more issues in power systems. Wind energy is one of the most promising renewable energies which could be utilized in power system to supply load demand. Installation of wind turbine generator (WTG) as a fuel saver and environment protector is too attractive since the manufacturing cost of WTGs is reduced. Computing the power output of a wind turbine generator is one of the most important issues which could affect the scheduling of the grid incorporated with wind farms. Many methods and models have been discussed in previous studies which are not accurate to predict the wind power output. This paper presents a new method to model power output of WTGs based on least square approximation and performance curve of the WTG which is given by the manufacturers. To demonstrate the capability of the method a case study composed of four WTGs with different power output each was conducted and the results have been compared with the previous models and found that this method is more accurate and reliable than other methods that have ever been introduced.

Index Terms*— *Hybrid Power System, Renewable Energy Sources, WTGs, linear Regression, Least Square Approximation.

I. INTRODUCTION

During the last decades by noticeable reduction of conventional resources in entire globe, many countries are trying to find successor energies, which have lower emission effects on the environment, affordable and also least cost to produce the electricity. Due to of reduce greenhouse gases usage of renewable energies as an alternative to produce electricity will be increased in the future and the role of renewable energies will become more important. Wind energy is one of the most attractive and fastest renewable energy sources due to of its abundance in nature and the maturity of its technology that could be utilized in power system to supply load demand. Installation of wind turbine generator (WTG) as a fuel saver is too attractive since the manufacturing cost of WTGs is reduced and causes considerable effects on social and economic of any developing countries [1, 2].

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Computing the power output of a wind turbine generator (WTG) is one of the most important issues which could affect the scheduling of the grid incorporated with wind farm and finding a proper method to model and convert wind energy to electricity is most significant and challengeable. Potential assessment of the wind power for installing WTGs and estimating WTGs output have been carried out by many studies. Power output of WTGs can be determined by various ways but it is necessary to model wind turbine power curve. Many methods and models have been discussed in previous studies which are not accurate to predict the wind power output [3]. Different models used to describe the performance of WTG by previous researchers. In wind energy engineering, wind speed distribution is modeled by the Weibull distribution and commonly used in the practical studies related to the wind energy modeling [4]. An investigation of wind characteristics and assessment of wind-generation was performed to evaluate the potential of wind energy [5]. In reference [6] authors introduced a method to find the capacity factor for site matching of offshore wind turbines. In reference [7] authors have discussed a method to determine pairing between sites and WTG. Some studies applied the performance curve of the turbine with piecewise linear function with a few nodes. Different studies assumed that wind power curve has a linear, quadratic or cubic relationship with wind speed. Most of previous studies showed and proved the fact, which is really vital to determine the accurate value of wind turbines energy output [8].The use of the manufacturer's power curve is the easiest approach to find the power output of WTG at the specific wind speed. However, for a specific WTG, a model should be developed according to its power output performance curve, which is given by the manufacturer [9]. This paper presents a new method to convert wind speed data to its corresponding wind power output of WTGs based on least square linear regression function and performance curve of the WTG which is given by the manufacturers. It is pivotal to mention, all simulations are performed in MATLAB and Microsoft office Excel to provide and deliver all the proposed concepts in suitable way.

II. PROBLEM FORMULATION

Traditionally, there are two types of WTGs which are variable-pitched and fixed-pitched.

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Variable-pitched is considered in this research because it tends to increase the range of cut-in and cut-out wind speed to "dump" power by controlling the blade's angle of attack by hydraulic and mechanical means. And it may take some time because of the large inertia of the rotor. Several turbine manufacturers were approached to "dump" power by means of pitch control [10, 11]. Induction generator type is preferred in this research due to being inexpensive, robust and that it does not require electrical connection between stator and rotor. The small wind variation will not also easily affect its operation [11]. Computing the power output of a wind turbine generator is one of the most important issues which could affect the scheduling of the grid incorporated with wind farms. Many methods and models have been discussed in previous studies which are not accurate to predict the wind power output.

The main objective of developing the model and algorithm is to find the accurate approach for converting the wind speed data to its corresponding wind power.

Least Square Approximation

Least square approximation have various types, the first order of them is straight-line approximation which is the simplest linear polynomial. Least squares straight-line approximations are a very profitable and widespread approximate fit. The least square straight-line fit can be determined and explained as follows. Suppose the given N is the numbers of observations (x_1, y_1), (x_2, y_2)… (x_n, y_n). The approximating function is [12]:

$$y = b + mx \quad (1)$$

For each value of x_i, Eq(1) gives

$$y_i = (b + mx_i) \quad (i = 1, \dots, N) \quad (2)$$

The amount of deviation e_i for each value of x_i is

$$e_i = (Y_i - y_i) \quad (i = 1, \dots, N) \quad (3)$$

The sum of the squares of deviations can be express the function S (b,m):

$$S(b, m) = \sum_{i=1}^{N}(e_i)^2 = \sum_{i=1}^{N}(Y_i - b - mx_i)^2 \quad (4)$$

When $\partial S/\partial b = \partial S/\partial m = 0$, the function S(b,m) is a minimum, therefore

$$\frac{\partial S}{\partial b} = \sum_{i=1}^{n} 2(Y_i - b - mx_i)(-1) = 0 \quad (5)$$

$$\frac{\partial S}{\partial m} = \sum_{i=1}^{n} 2(Y_i - b - mx_i)(-x_i) = 0 \quad (6)$$

The normal equations of least-squares approximations can be expressed as follows [12]:

$$bN + m\sum_{i=1}^{N} x_i = \sum_{i=1}^{N} Y_i \quad (7.a)$$

$$b\sum_{i=1}^{N} x_i + m\sum_{i=1}^{N} x_i^2 = \sum_{i=1}^{N} x_i Y_i \quad (7.b)$$

Let Y_i represent an experimental value, and let y_i be a value from the Eq.(2), where x_i is a particular value of the variable assumed to be free of error. e_i minimize the sum of the squares of the deviations, b and m are the constants that can be determined by Eq.(7).

Wind power output is function of wind speed and usually could be approximated to be linear, quadratic or cubic function of wind speed and Eq. (1) illustrates the general function of wind power output. In this study, wind power curve was approximated to be linear function of the wind speed.

$$P^*_{W_j}(t) = \begin{cases} 0, & V(t) \le V_{I_j}, V(t) > V_{O_j} \\ M_j(V(t)), & V_{I_j} < V(t) \le V_{R_j} \\ P^{max}_{W_j}(t), & V_{R_j} < V(t) \le V_{O_j} \end{cases} \quad (8)$$

$$M_{nj}(V(t)) = \begin{cases} a_1 V(t) + b_1, & V_{I_j} \le V(t) \le V_{1_j} \\ \vdots \\ a_n V(t) + b_n, & V_{n_j} \le V(t) \le V_{R_j} \end{cases} \quad (9)$$

In Eq. (8) $M_{nj}(V(t))$ is approximated by a piecewise linear least square and given in Eq. (9), $P^{max}_{W_j}(t)$ is the wind generator rated power output and V_{I_j}, V_{R_j}, V_{O_j} are the wind generator cut-in, rated and cut-out wind speeds respectively. From Eq. (9) $V(t)$ is the predicted wind speed, $V_{1_j}, \dots, V_{n_j}$ are given wind speed by manufacturer in performance curve of the turbine, $a_1, \dots, a_n$ and $b_1, \dots, b_n$ are the coefficients of linear function and can be obtained by least square approximation which explained above and power performance curve of the specific turbine.

III. APPLICATION AND RESULTS

To demonstrate the capability of the method a case study composed of four different classes of WTGs E33-330, E53-800, E82-2000 and E101-3000KW of Enercon was conducted. In this study, seven models of previous studies which are given below [3] applied and finally compared with the method Eq. (9) (M_8) which is discussed in this research.

$$M_1 = P_R * \left(\frac{V - V_I}{V_R - V_I}\right) \quad (10)$$

$$M_2 = (a_1 V^2 + a_2 V + a_3) \quad (11)$$

$$M_3 = P_R * \left(\frac{V^2 - V_I{}^2}{V_R{}^2 - V_I{}^2}\right) \quad (12)$$

$$M_4 = P_R * \left(\frac{V^3}{V_R{}^3}\right) \quad (13)$$

$$M_5 = P_R * \left(\frac{V - V_I}{V_R - V_I}\right)^3 \quad (14)$$

$$M_6 = (b_1 V^3 + b_2 V^2 + b_3 V + b_4) \quad (15)$$

$$M_7 = (c_1 V^4 + c_2 V^3 + c_3 V^2 + c_4 V + c_5) \quad (16)$$

Results are given in Tables (1) to (4) and show the comparison of different methods for various WTGs. Figs. (1) to (4) indicate the graphical comparison of proposer and different previous methods. Table 5 and Fig. 5 show the mean deviation of the rated and estimated powers of selected WTGs for different developed methods and this study.

$$WTG\ Dev = P_R - P_{estimated} \quad (17)$$

$$\text{WTG}\ Mean\ Dev = \frac{\sum Dev}{number\ of\ observation} \quad (18)$$

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Table 1. Comparison of Linear Least Square Approximation and Previous Models for WTGs EE33-330 KW

Speed[m/s]	Power[KW]	M1[KW]	M2[KW]	M3[KW]	M4[KW]	M5[KW]	M6[KW]	M7[KW]	M8[KW]
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	5	0	0	0	0	0	10.748	6.05	5
4	13.7	33.5	12.69	14.65	9.76	0.335	7.57	12.27	14
5	30	67	42.52	33.5	19.06	2.68	23.74	28.44	30
6	55	100.5	74.62	56.53	32.93	9.045	54.99	55.77	55
7	92	134	108.99	83.75	52.30	21.44	97.05	93.92	92
8	138	167.5	145.65	115.15	78.07	41.87	145.65	140.95	138
9	196	201	184.58	150.75	111.16	72.36	196.53	193.40	196
10	250	234.5	225.80	190.53	152.48	114.90	245.42	246.21	250
11	292.8	268	269.29	234.5	202.95	171.52	288.06	292.76	293
12	320	301.5	315.06	282.65	263.48	244.21	320.18	324.88	320
13	335	335	335	335	335	335	337.51	332.82	335
14	335	335	335	335	335	335	335	335	335

Table 2. Comparison of Linear Least Square Approximation and Previous Models for WTGs EE53-800 KW

Speed[m/s]	Power[KW]	M1[KW]	M2[KW]	M3[KW]	M4[KW]	M5[KW]	M6[KW]	M7[KW]	M8[KW]
1	0	0	0	0	0	0	0	0	0
2	2	0	-46.96	0	2.949	0	29.05	1.891	2
3	14	73.64	1.232	24.55	9.954	0.609	-5.678	16.541	14
4	38	147.3	57.05	58.91	23.6	4.869	8.682	35.839	38
5	77	220.9	120.5	103.1	46.09	16.43	62.91	73.612	77
6	141	294.5	191.6	157.1	79.64	38.95	147.8	137.93	141
7	228	368.2	270.3	220.9	126.5	76.07	254.1	231.1	228
8	336	441.8	356.6	294.5	188.8	131.5	372.7	349.67	336
9	480	515.5	450.5	378	268.8	208.7	494.3	484.43	480
10	645	589.1	552.1	471.3	368.7	311.6	609.7	620.4	645
11	744	662.7	661.3	574.4	490.7	443.6	709.7	736.85	744
12	780	736.4	778.2	687.3	637.1	608.6	785.1	807.29	780
13	810	810	810	810	810	810	810	799.46	810
14	810	810	810	810	810	810	810	810	810

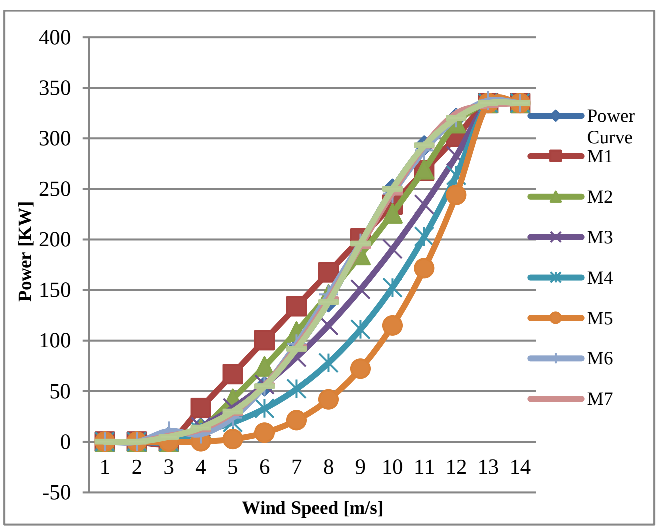

Fig. 1. Graphical Comparison of EE33-330 KW

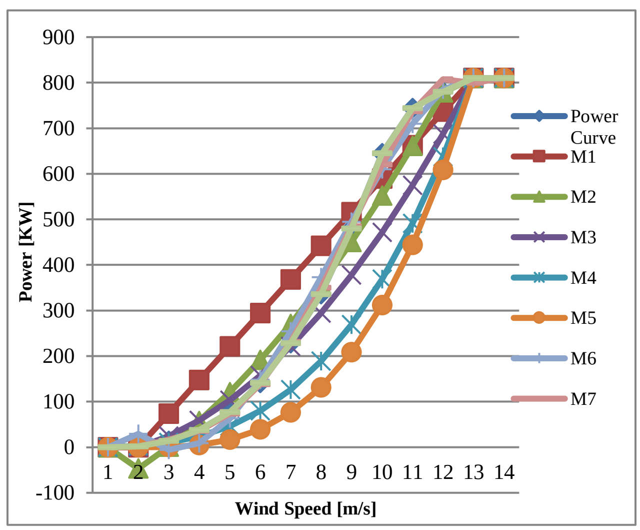

Fig. 2. Graphical Comparison of EE53-800 KW

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Table 3. Comparison of Linear Least Square Approximation and Previous Models for WTGs EE82-2000 KW

Speed[m/s]	Power[KW]	M1[KW]	M2[KW]	M3[KW]	M4[KW]	M5[KW]	M6[KW]	M7[KW]	M8[KW]
1	0	0	0	0	0	0	0	0	0
2	3	0	-111.38	0	7.46	0	68.45	2.95	3
3	25	186.36	-5.24	62.12	25.19	1.540	-21.59	32.00	25
4	82	372.73	123.09	149.09	59.718	12.32	8.65	74.16	82
5	174	559.09	273.62	260.91	116.64	41.58	137.38	163.19	174
6	321	745.45	446.35	397.57	201.55	98.57	342.81	318.99	321
7	532	931.82	641.28	559.09	320.05	192.52	603.14	547.55	532
8	815	1118.18	858.41	745.45	477.74	332.68	896.55	840.97	815
9	1180	1304.54	1097.73	956.66	680.22	528.28	1201.27	1177.45	1180
10	1580	1490.91	1359.25	1192.72	933.09	788.58	1495.49	1521.29	1580
11	1810	1677.27	1642.97	1453.63	1241.94	1122.80	1757.41	1822.92	1810
12	1980	1863.64	1948.89	1739.39	1612.38	1540.19	1965.24	2018.83	1980
13	2050	2050	2277	2050	2050	2050	2097.17	2031.66	2050
14	2050	2050	2050	2050	2050	2050	2050	2050	2050

Table 4. Comparison of Linear Least Square Approximation and Previous Models for WTGs EE101-3000 KW

Speed[m/s]	Power[KW]	M1[KW]	M2[KW]	M3[KW]	M4[KW]	M5[KW]	M6[KW]	M7[KW]	M8[KW]
1	0	0	0	0	0	0	0	0	0
2	3	0	-166.34	0	11.11	0	118.77	-14.99	3
3	37	277.27	-12.58	92.42	37.48	2.29	-38.50	70.94	37
4	118	554.54	176.33	221.82	88.85	18.33	-5.10	128.65	118
5	258	831.82	400.40	388.18	173.53	61.87	184.40	237.1	258
6	479	1109.09	659.62	591.51	299.86	146.66	495.47	446.83	479
7	790	1386.36	954.00	831.82	476.17	286.44	893.52	780.03	790
8	1200	1663.64	1283.53	1109.09	710.78	494.96	1344.01	1230.52	1200
9	1710	1940.90	1648.22	1423.33	1012.04	785.99	1812.38	1763.74	1710
10	2340	2218.18	2048.06	1774.54	1388.26	1173.25	2264.05	2316.75	2340
11	2867	2495.45	2483.05	2162.75	1847.77	1670.51	2664.49	2798.25	2867
12	3034	2772.72	2953.2	2587.88	2398.91	2291.51	2979.12	3088.56	3034
13	3050	3050	3458.5	3050	3050	3050	3173.38	3039.62	3050
14	3050	3050	3050	3050	3050	3050	3050	3050	3050

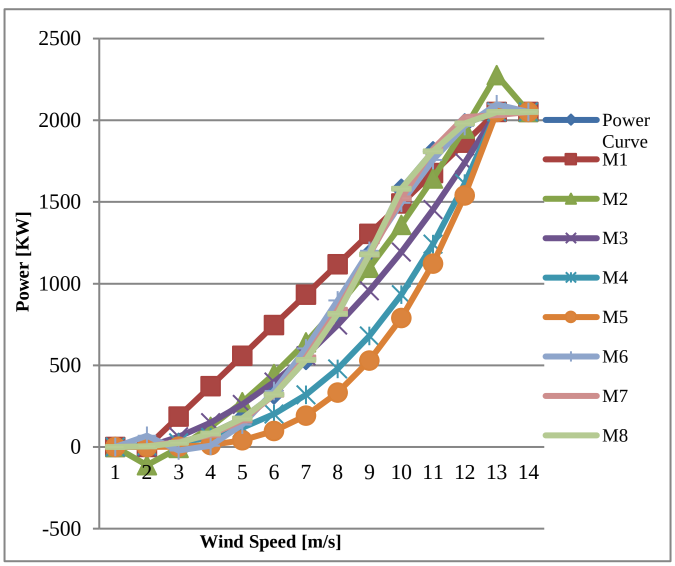

Fig. 3. Graphical Comparison of EE82-2000 KW

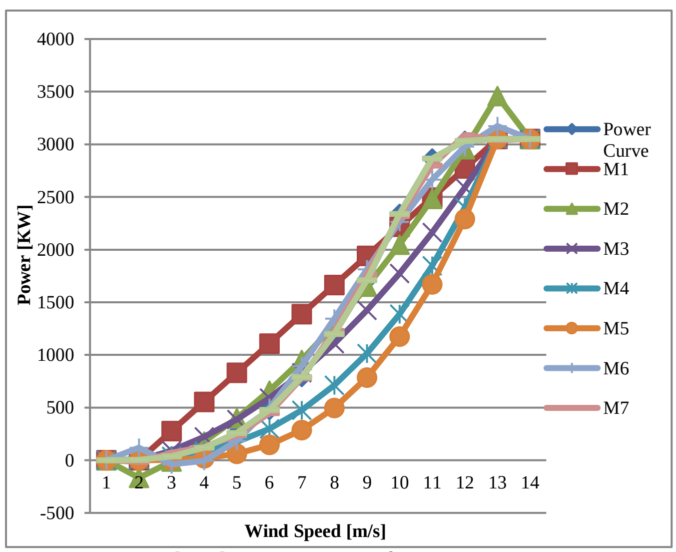

Fig. 4. Graphical Comparison of EE101-3000 KW

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Table 5. Comparison of Applied Methods' Deviation

Method	EE33-330 KW	EE53-800 KW	EE82-2000 KW	EE101-3000 KW
M1	22.054	77.553	202.53	327.439
M2	11.530	37.045	107.628	172.899
M3	22.040	55.189	131.242	211.681
M4	42.754	103.682	236.277	367.367
M5	64.92	137.007	320.242	492.015
M6	3.943	20.73	51.401	100.923
M7	2.105	8.504	16.714	30.568
M8	0	0	0	0

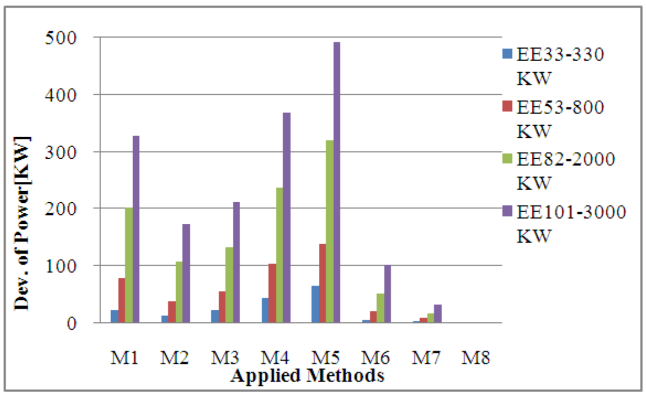

Fig. 5. Graphical Comparison of Applied Methods

IV. CONCLUSION

On the basis of the introduction a novel method based on least square approximation to estimate the power output of WTG by using its power performance curve was presented. In this research, practical calculated power curve and limitations of each WTG were included. This method is programmed in MATLAB and Excel software area and applied to a case study with four different classes of WTGs to show the capability of the proposed method and finally compared with seven previous models. In this study, for simplicity only the region between cut-in and rated wind speed was considered. From the Fig. and table of deviations, it can be seen that M8 does not have any deviation or can be neglected but other models have much deviation from the actual amount. From the results, it can be seen that models M7, M6, M2, M1, M4 and M5 have less deviation from actual given amount respectively. It means these models are not accurate to estimate the power output and will cause increases in cost analysis. In this study, the proposed model has found better solution than other methods which is capable to determine the most accurate power output and it is essential to mention that accuracy of the model will cause reduction in cost analysis and better estimation for future developments. In this case, it has shown that deviation of the models M1 to M7 were increased by increasing the capacity of the WTGs but the proposed model has zero deviation increase, which means this method is more appropriate than others. In this paper, the WTG power output was estimated through interpolation of the values of the data provided by the manufacturers in few nodes and intervals. Therefore, M8 has any or lower deviation among all the models and results are the same as actual ones.

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