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A simple new method for wind farm power curve development: A case study

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Abstract

Wind farm power curve is an essential tool in forecasting wind power and evaluating performance of the wind farm. This study investigates the simple method to develop accurate wind farm power curve. Four methods are used to develop power curves. Three of them are traditional methods the other is a new proposed method. New method is a combination of traditional statistical and physical methods. Statistical part of this new method is based on International Electrotechnical Commission standards. Physical part of new method is obtained from Wind Atlas Analysis and Application Program (WASP). Real site measurements are used to evaluate method performances. Test results showed that performance of the proposed method is better than three traditional methods.'

Keywords: Wind farm power curve, wind farm performance, wind power forecast, wind farm model.

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1. INTRODUCTION

Over the last decade wind energy has been the most prominent renewable energy resource [1]. Promoting policies of countries and decrease in installation costs increased the total installed capacity of wind energy all around the world. This rapid increase caused some new problems. It is well known that wind energy has variable, uncertain nature. So it is not easy to balance electrical grid that has high wind penetration [2].

Transmission system operators (TSO) must ensure and maintain the balance between supply and demand in their electrical grids. So they have to make accurate generation plans to achieve balanced system. Wind energy forecasts help TSO to create day ahead or intraday generation plan. Within this scope numerous of studies on wind power forecast have been carried out, Giebel and Brownsword et all summarized them [3]. Forecast systems use wind farm power curves to convert forecasted wind speed and direction to electrical power. So quality of power curve has an impact on performance of the forecast. On the other hand wind farm owners want to evaluate the performance of their power plant. Wind farms will have clusters of wind turbines spread over a large terrain. It is not easy to collect data from numbers of turbines. The single accurate power curve will shorten this process. It is clear that wind farm power curve is an essential tool for wind farm management and wind energy forecasting [4].

Developing a power curve for a wind farm is not an easy process. Because lots of parameters like air density, topographical obstacles, wake effects, wind direction etc. have impact on wind speed - power

output relation. Also turbine clusters will spread over a large area and site conditions differ cluster to cluster. On the other hand it is necessary to have accurate site measurements to develop a wind farm power curve. Hard weather conditions like icing, very high wind speeds etc. make difficult get accurate measurement data.

In this study we developed wind farm power curves. Real site measurements are used to develop and test power curves. Wind speed - power and wind speed, direction – power relations are investigated. Literature review showed that studies in this topic mostly focused on statistical methods in applications [5-12]. Four methods are used to develop power curves in our study. Two of them are simple statistical methods. Third method is based on physical model approach. WASP software is used to get physical model. The last one is proposed new method. It is the mix of statistical and a physical methods. Details of four methods and site measurement process are given in the next sections.

Aim of the study is to investigate powerful method to develop accurate wind farm power curve. A new method is proposed and results are compared with traditional ones.

The rest of this paper is structured as follows: Section II describes the experimental wind farm and measurement process; Section III describes details of methods; results are given in Section IV; Section V includes conclusions of the study.

2. WIND FARM AND MEASUREMENTS

2.1 Wind Farm

Wind farm is located at the Marmara Region of Turkey. Due to commercial restrictions exact location and name of the plant is not mentioned. Farm has five turbines (Vestas V90). Technical characteristics of turbine are summarized in Table 1. Total installed capacity of wind farm is 15 MW. Annual energy production is nearly 52 GWh. Power plant is visualized on Google Earth screen as in Fig. 1.a. Wind frequency roses of turbines and power density map of plant area based on measured data are given in Fig. 1.b.

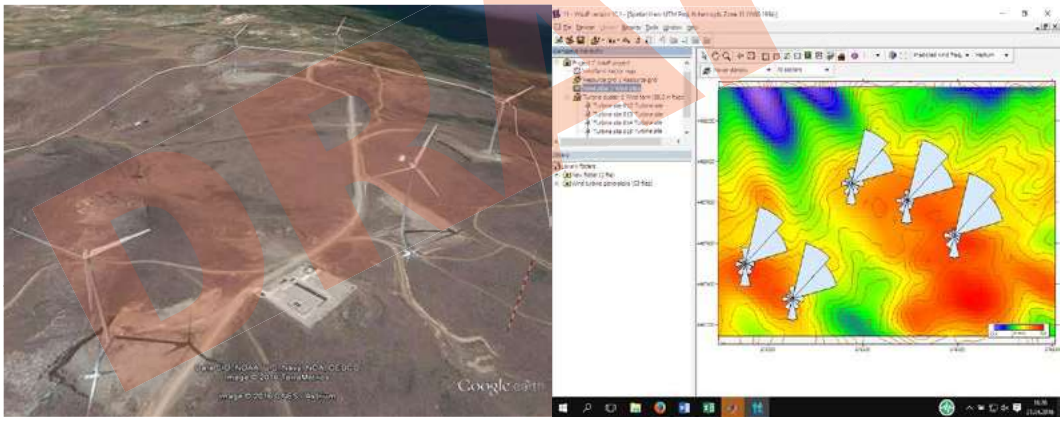

Figure 1: a) Wind Farm on Google Earth screen b) Power density map and wind frequency roses

Table 1. Turbine characteristics

Turbine Characteristic	Rated Value
Rated power (MW)	3.0
Turbine type	Horizontal
Hub height (m)	80
Rotor diameter (m)	90
Swept area (m2)	6362
Cut in wind speed (m/s)	3.5
Rated wind speed (m/s)	15
Cut out wind speed (m/s)	25

2.2 Measurements

Two kinds of measurement stations were installed during the development stage of the wind energy monitoring and forecasting system for country. They are an electrical power and meteorological data measurement stations. Electrical power measurement station is located in the powerhouse of the plant.

This equipment also measures electrical power quality quantities in accordance with IEC standard [13]. Meteorological measurement mast is located at the plant area. Mast is installed in accordance with IEC standard [14]. Some characteristics of mast are given in Table 2. Location of the mast can be seen in Fig. 1.a. (red and white colored tower is mast). According to IEC standard distance between mast and nearest wind turbine will be 2.5 times rotor diameter. Turbines and mast are located on topographical map as in Fig. 2. Diameters of grey circles are 2.5 times rotor diameter. General view of mast is given in Fig. 2.

GPS time synchronization equipment was used to synchronize meteorological and electrical power data. Thanks to this process there is no time shifting between two data. Sampling and recording periods are 1 and 15 seconds. System stores data in data logger and also sends it via GPRS modem to monitoring and forecasting system center (located in capital city of Turkey, Ankara)

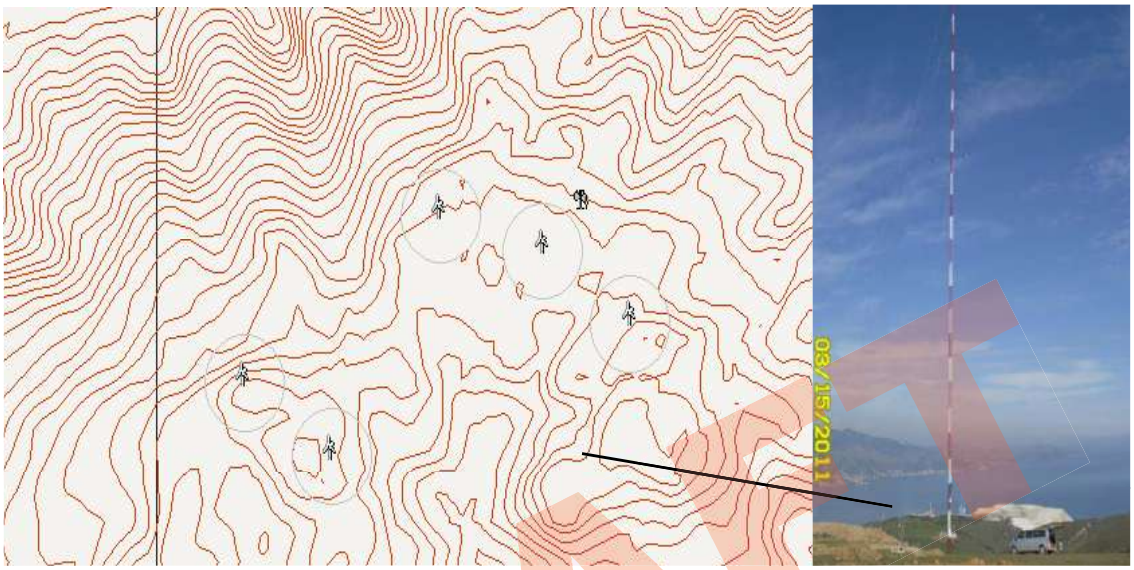

Figure 2: Turbines and mast on map.

Table 2. Mast characteristics

Equipment	Number	Installed Height (m)
Anemometer	6	80, 65, 50
Wind vane	2	78, 48
Humidity and temperature sensor	1	8.5
Pressure sensor	1	7
Data logger	1	7

2.3 Measured Data

It is desired to have at least one year period of data to capture seasonal effects on wind farm performance. Wind farm performance also has an impact on power curve. But it is not easy to record uninterrupted annual meteorological data due to hard weather conditions. Icing is most prominent bad condition for mast. Installed mast system has an algorithm to detect anomalous measurement. Algorithm compares anemometer data with others, if difference is big software labels data as bad measurement. Thanks to this it is easy to filter unreliable data. Some characteristics of measured data are summarized in Table 3.

Table 3. Mast characteristics

Equipment	Number
Data interval	22.01.2016 00:00 – 01.06.2014 00:00
Number of data	86400
Data averaged period	10 minutes
Availability	%66.32

Anomalous measurements of mast are filtered. Also mismatches due to turbine failure and maintenance works are filtered too. As a result of these rejections 57298 data is available. Scatter plot of measured wind speed, direction and electrical output is given in Fig. 3.

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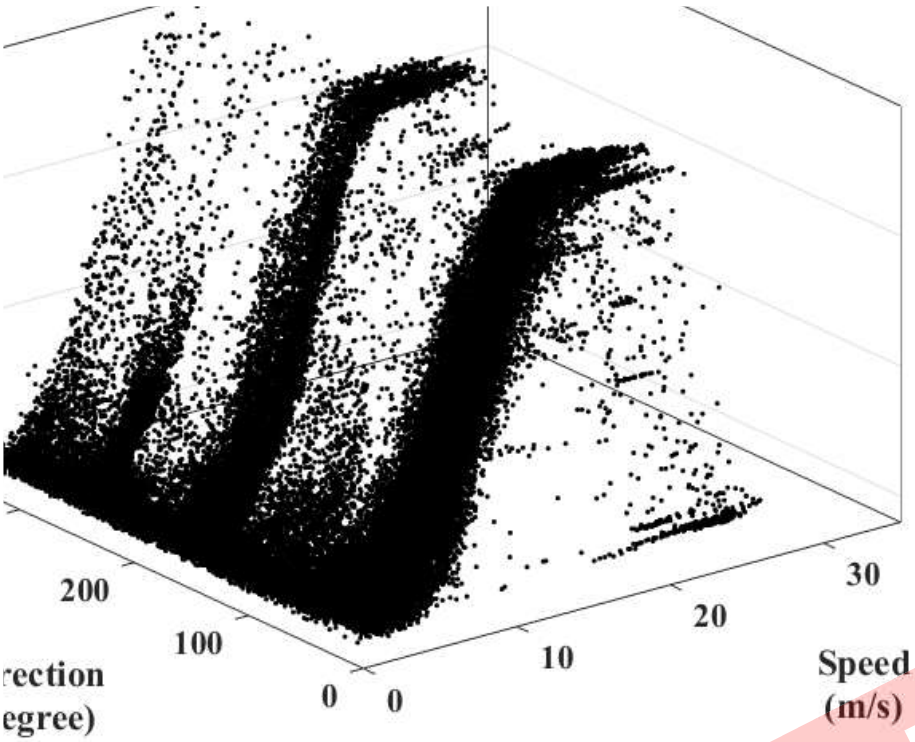

Figure 3: Scatter plot of measured wind direction, wind speed and electrical power data.

3. METHODS

Nomenclature	
bs:	Bin number of wind speed
bd:	Bin number of wind direction
N:	Number of data
S:	Wind speed
D:	Wind direction
P:	Electrical power
CM:	Corrector matrix
WPM:	Power matrix of WAsP
MAE:	Mean absolute error
RMSE:	Root mean squared error
SDE:	Standard deviation of error

Three general power curve development approaches and one proposed method are used to obtain wind farm power curve. First and second approaches are based on IEC standards [11,14]. First one is mean bin method. It is the result of direct relation between averages of measured wind speed and electrical power data for each wind speed bin. Bin width is selected as 0.5 (m/s). Simple formulation of this method is given in Eq.(1) and Eq.(2). Averaged value of wind speeds and electrical powers for each bin constitutes power curve.

$$V_b = \frac{1}{N_b}\sum_{k=1}^{N_b} V_{b,k} \tag{1}$$

$$P_b = \frac{1}{N_b}\sum_{k=1}^{N_b} P_{b,k} \tag{2}$$

Second method is similar to first one. This approach considers wind direction and speed values. Wind speed, wind direction and power values are averaged for each speed and direction bin. Bin widths of speed and direction are 0.5 (m/s) and 30 (). Result of this method gives a matrix that relates wind speed and direction pairs with electrical power. Formulation of method is given in Eqs. (3) – (5).

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$$V_{bv} = \frac{1}{N_{bv}} \sum_{k=1}^{N_{bv}} V_{bv,k} \quad (3)$$

$$D_{bd} = \frac{1}{N_{bd}} \sum_{k=1}^{N_{bd}} D_{bd,k} \quad (4)$$

$$P_{bv,bd} = \frac{1}{N_{bv,bd}} \sum_{k=1}^{N_{bv,bd}} P_{bv,bd,k} \quad (5)$$

Averaged values for each wind speed bin are calculated in right side of Eq.(3). Same calculations for direction bins are in Eq.(4). At the right side of Eq.(5), averaged electrical power outputs for each wind speed and direction bin pairs are calculated. Third approach is based on physical model. Model is obtained from WASP. Power curve is matrix as in second method. WASP considers orographic impact on power curve. This is the distinctness of this method. But software uses manufacturer wind turbine power curves not side performances of turbines. This reason causes errors. Last approach is proposed one. This is the mix of second and third method. Orographic impact and site measurements are considered. At first step WASP power curve is obtained. At second step software power curve is corrected by corrector matrix. Corrector matrix elements are averages of differences between actual value and calculated value from software power curve for each speed and direction bin.

$$CM(V_{bv}, D_{bd}) = \frac{1}{N_{bv,bd}} \sum_{k=1}^{N_{bv,bd}} [P_{bv,bd} - WPM(V_{bv}, D_{bd})] \quad (6)$$

Eq.(6) gives the each element of corrector matrix. Sum of corrector matrix and software matrix constitutes wind farm power curve.

4. RESULTS

Three general and a proposed method to obtain wind farm power curve are investigated. Performances are summarized in Table 4. RMSE, MAE and SDE are used as performance indices. Also histograms of error distributions are given in Fig. 4.

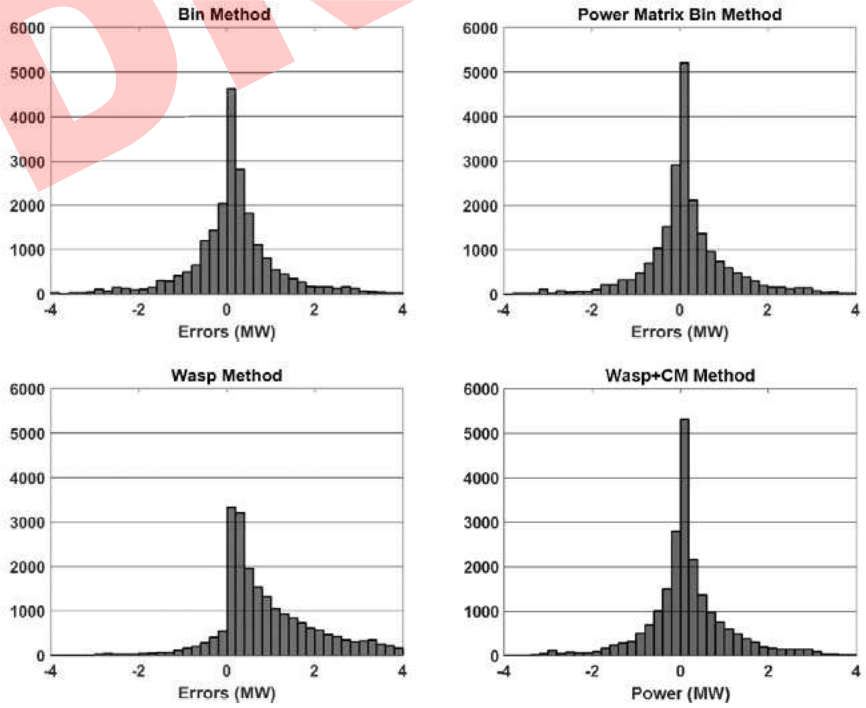

Figure 4: Histograms of errors.

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Table 4. Performances of Methods

Method	MAE	RMSE	SDE
Mean Bin	5.108	8.798	8.782
Power Matrix Bin	4.781	8.630	8.590
Wasp	8,197	12,267	10,233
Wasp +CM	4,743	8,396	8,343

Site measurement data sets of wind speed, wind direction and generated power are used to evaluate them. First method relates wind speed and power output. It is well known that there is a cubic order relation between wind speed and wind power. Due to this strong relation this approach gives good results. Second approach considers the directional change of wind speed – wind power relation. This consideration improved the performance. Third and fourth approaches consider orographic effects on power curve. Proposed fourth method is combination of third and second one. Wasp matrix includes orographic effects and corrector matrix includes statistical results. This approach gives best result when compared with other three investigated methods. This will be a simple power curve development method for similar wind farms.

5. CONCLUSİON

This paper has investigated approaches on wind farm power curve development. A proposed new approach is combination of statistical and physical approaches. Results showed that performance of this new is method is better than other methods applied in this study. Statistical and physical parts of proposed method are based on very simple approaches. More advanced statistical and physical parts will improve the performance of the new method.

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