Equivalent Power Curve Model of a Wind Farm Based on Field Measurement Data

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***Abstract*—This paper discusses how a simple equivalent model of a whole wind farm can be obtained using field measurement data for individual wind turbines at the site. The equivalent model, which is formulated as a power curve, is specifically intended for steady state performance assessment, i.e. estimation of annual energy production of the wind farm. Two general approaches for building the equivalent steady state model of the wind farm are analysed: a) aggregate-measured power curve, obtained as an averaged aggregate representation of the outputs from all wind turbines, and b) cluster-measured power curve, obtained using the support vector clustering technique. Recorded measurement data from two actual wind farms are used to perform the analysis and to validate the results, where the accuracy of both proposed methods is assessed by direct comparison with the available recordings.**

***Index Terms*—Distributed power generation, power curve, steady state power system analysis and modelling, wind-based power and energy generation, wind farm, wind turbine.**

I. INTRODUCTION

THE European standard EN 61400-12-1 [1] specifies a general procedure for measuring performance characteristics (i.e. output power) of a single wind turbine (WT) connected to electrical network. The standard acknowledges the fact that the actual performance of the WT in a particular target application, represented as a "measured power curve", may be different from the one specified by the manufacturer ("manufacturer power curve"). The measured power curve of an individual WT is determined by collecting simultaneous measurements of input wind speeds and output powers for a long enough period of time, and can be used to estimate the energy production of a wind turbine. The standard [1], however, does not discuss how this approach can be generalized and used for modelling or representing the whole wind farm with one or more equivalent WTs and corresponding measured power curve(s).

Power curves of WTs specified by the manufacturers are commonly used in network studies, e.g. to estimate the production from a particular wind site during the planning or general design phase, or when there are no other available wind farm output data (e.g. [2], [3]). However, manufacturer power curves are obtained in controlled conditions (e.g. in air-tunnels), where the effects of short-term wind speed/direction variations, presence of turbulence, overall dynamics of WT and other site/application specific factors are usually not fully represented [3], [4]. Consequently, if the manufacturer power curve is used for estimation of energy production, this will typically result in overestimated energy outputs [5].

This paper addresses the problem of obtaining a simple and accurate equivalent model of a wind farm, which is an issue of interest for both planning and operation of wind farms. The methodology presented uses recorded input wind speed and output power data from two actual wind farms to develop accurate steady state equivalent models for the estimation of energy outputs. Section II of this paper presents a brief overview of the aggregation methods used in the literature and proposes two methods for obtaining equivalent wind farm models. Section III describes the equivalent power curves of individual WTs (one from each of analysed wind farms), as well as of two considered wind farms. The results of the two equivalenting methods are discussed in Section IV, providing comparisons of estimated energy outputs for different sets of data, wind speed measurements at the mast, at the nacelle and for recalculated wind speeds in front of the WT blades. The last section of the paper provides discussion of the results, general comments and recommendations for further work.

II. AGGREGATION OF WT DATA AND EQUIVALENT MODEL

Various methods for equivalenting wind farms have been presented in the literature and applied for steady state and dynamic analysis, with an overview of current methods provided in [6]. It is recommended that smaller wind farms should be modelled as a single lumped equivalent, assuming that the power fluctuations from each WT more or less coincide. Larger wind farms, with a greater geographical spread, should be aggregated using one equivalent model for each radial line (in cases where the wind farm layout is arranged in a radial network) or group of WTs at the end of a major feeder. A single equivalent model has also been developed in [7], while aggregation of WTs based on identical incoming wind speeds has been carried out in [8] and [9]. Similarly, a coherency method has been implemented in [10] to identify groups of WTs with similar input wind speeds. In [11] equivalent models have been obtained after considering wind speed profiles affected by multiple wake effects and wind directions of individual WTs as input data for a clustering algorithm. Although these methods for equivalenting wind farm have been verified as being acceptable for representing large wind farms with a reduced configuration, more tests

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would be needed to assess their performance in applications to wind farms with different characteristics.

Implementation of the developed equivalent wind farm models is an important question, where particularly applications of interest to investors and wind farm owners/operators have a high practical value. Accordingly, this paper presents a simple, efficient and accurate methodology for equivalenting a wind farm, which is specifically intended for the calculation/estimation of annual wind farm energy outputs. The equivalent wind farm model is given in the form of one or more power curves, obtained from the available measurement data for individual WTs within the wind farm. A "power curve representation" is selected as the output of the proposed modelling method, as power curve is not just a simple and straightforward way for describing the performance of a wind-based generation system, but is also a commonly used tool for estimation of corresponding energy outputs. Two proposed methods for creating equivalent power curve models of a wind farm are discussed below.

A. *Aggregate-measured power curve*

Perhaps the simplest way to model a wind farm is to represent the whole wind farm with a single equivalent WT and corresponding equivalent power curve. This equivalent WT will have rated power equal to the sum of the rated powers of all individual WTs within the wind farm. That approach is denoted as "aggregate-measured power curve (AMPC)" method in this paper, where the equivalent WT power curve is established by averaging past simultaneous measurements of input wind speeds and output powers of all WTs in wind farm.

B. *Cluster-measured power curves*

The second approach proposed in this paper for equivalenting a wind farm is based on the application of clustering technique for identifying one or more equivalent power curves. For that purpose, the support vector clustering (SVC) algorithm is used to create distinctive non-overlapped classes of wind speed and/or power output profiles. SVC consists of the determination of the support vectors (SVs) and cluster labelling characterised by the identification of the final clusters. During the first stage of the SVC algorithm [12], two types of data features are identified, namely SVs and bounded SVs. At the second stage (cluster labelling stage), final clusters are formed using a deterministic procedure described in [13].

The first step in creating aggregate power curves using the SVC algorithm is to assign the WTs with the same wind/power profiles to clusters, where created groups of WTs are considered to be aggregate models of the analysed wind farm. The corresponding cluster-measured power curves (CMPCs) are formed by averaging the sum of the input wind speeds and power outputs of the WTs grouped together as a result of the clustering procedure.

III. EQUIVALENT POWER CURVE MODELS OF TWO WIND FARMS

The performance of the two proposed methods for obtaining accurate steady state equivalent wind farm models is tested on two wind farms with total installed powers of 18 MW and 27.2 MW, each with very different characteristics.

A. *Description of the wind farms used in the analysis*

The first set of data is taken from a UK wind farm consisting of 6 x 3MW WT units with doubly-fed induction generators (DFIGs), sited on a relatively flat terrain. The available input wind speeds and power outputs of individual WTs are recorded as average 10-minute values over a period of three years. The second set of data has been collected during a period of around six months from a wind farm located in Italy on a very irregular and hilly terrain. This wind farm consists of 32 DFIG-type WTs, each with a rated power of 850 kW. The whole wind farm is divided in three wind parks: the first and second have 11 WTs, while the third has 10 WTs. The layout of both wind farms is shown in Fig. 1.

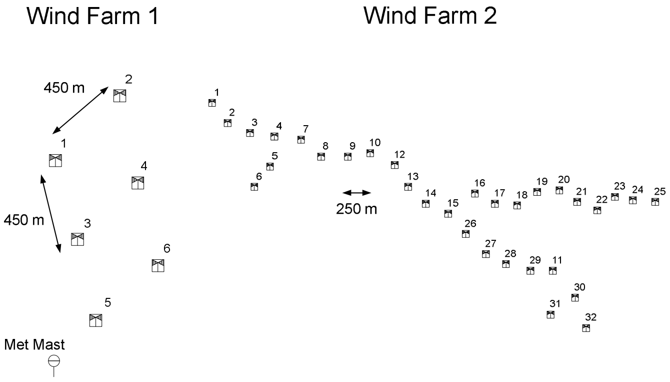


Fig. 1. Layout of the UK (Wind Farm 1) and Italian (Wind Farm 2) sites (not to scale).

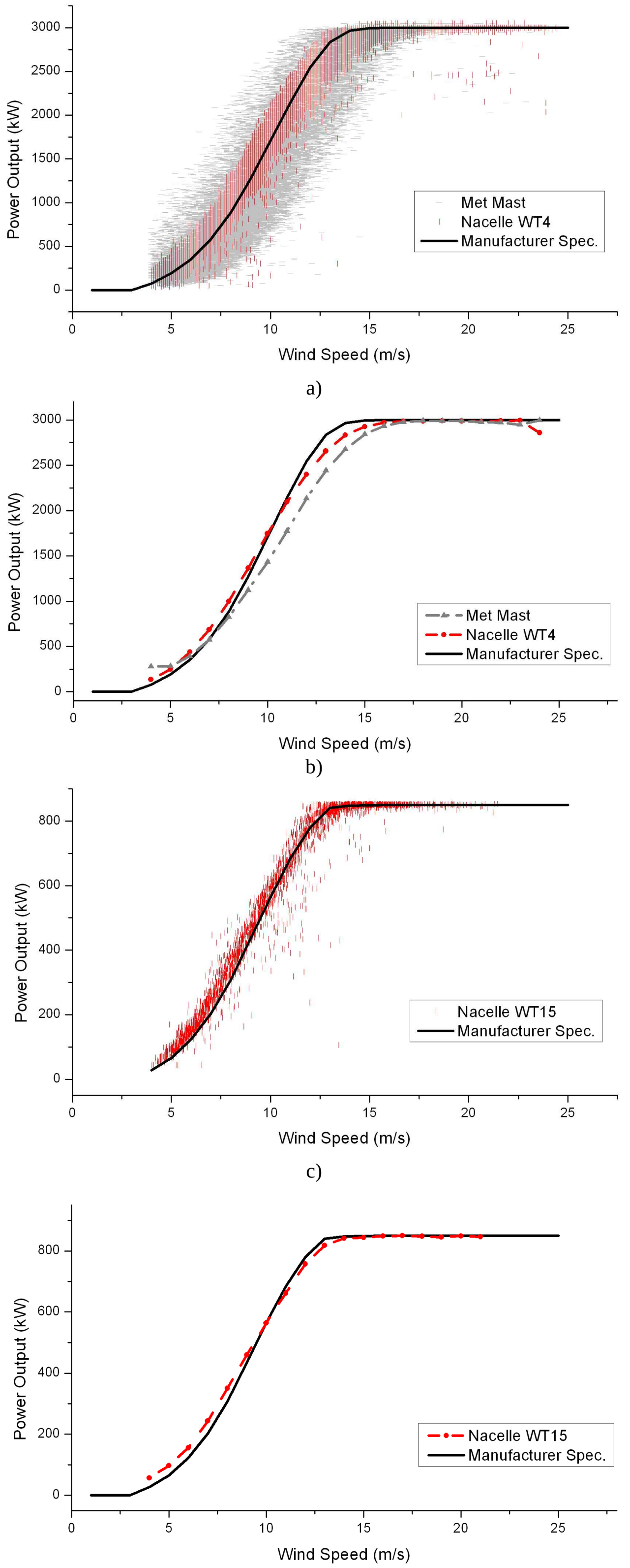
B. *Measured power curves of individual WTs*

Based on the available recordings for individual WTs, the measured power curves can be obtained and then used to compare estimated energy outputs with those obtained using manufacturer power curve. Fig. 2 compares manufacturer power curves with actual measurements (Fig. 2a and 2c), and corresponding measured power curves for nacelle or mast measured wind speeds for two individual WTs from both analysed wind farms (Fig. 2b and 2d).

In Fig. 2, WT4 is from the 18 MW wind farm, where wind speeds were measured both at the nacelle and at an on-site anemometer mast. WT15 is from the 27.2 MW wind farm, where wind speeds are recorded only at the nacelle. Figs. 2b and 2d show measured power curves for two individual WTs obtained using the "method of bins" [1], where each "bin" represents one specific wind speed from the selected range of measured values:

$$V_{i=}\left(\sum_{j=1}^{N_i} V_{i,j}\right)/N_i,\ P_{i=}\left(\sum_{j=1}^{N_i} P_{i,j}\right)/N_i\ \text{, for } i=1,\ldots,n \qquad (1)$$

where: V_i, P_i - average values of all measured wind speeds and power outputs allocated to bin i; $V_{i,j}$, $P_{i,j}$ - measured j–th values of wind speed and power output in bin i; N_i - total number of measured values in bin i; n – totals number of bins. The bin size used is 0.5 m/s, which gives a total of 51 bins for the considered range of wind speeds from 0 to 25 m/s.



a)

b)

c)

d)

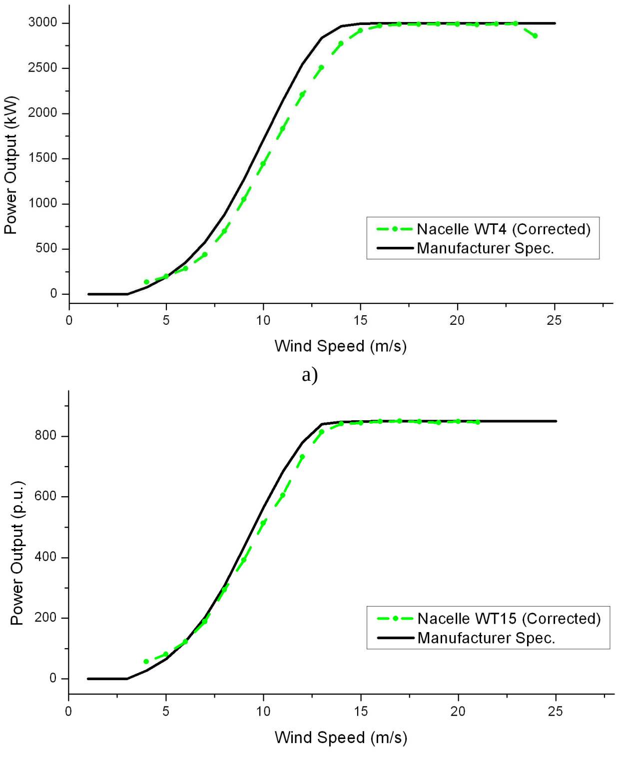
Fig. 2. Comparison of recordings with manufacturer and measured power curves for individual WTs at each site: a) manufacturer power curve and recorded data for wind speeds measured at the nacelle of WT4 and mast for the UK site, b) manufacturer power curve and measured power curves reconstructed from the recorded data using the "method of bins" [1] for WT4, UK site; c) manufacturer power curve and recordings at the nacelle of WT15 from the Italian site; d) “method of bins” applied to WT15.

The differences between the measured power curves for wind speeds recorded at the nacelle and at the mast (Fig. 2b) are as expected. WT4 is located at a distance of approximately 1 km from the mast, where the wind speed profile at the turbine nacelle is different than at the mast. Additionally, even in cases when the mast is located in the vicinity (i.e. in front of the analysed WT), there will be differences between the two measurements, as the wind speed measured by the anemometer at the nacelle is generally lower than the actual wind speed in front of the WT blades due to changes in the air stream characteristics when the air passes through the blades.

In order to illustrate this, the wind speed measured at the nacelle is corrected to give an accurate representation of the actual wind speed in front of the blades. For that purpose, the method outlined in [14] is used:

$$s_{w,IN} = \sqrt[3]{\frac{\dfrac{P_{el}}{\eta_{gear}\cdot\eta_{DFIG}} + \dfrac{1}{2}\cdot\rho_{air,ACT}\cdot\dfrac{\pi}{4}\cdot D_{OUT}^{2}\cdot s_{w,OUT}^{3}}{\dfrac{1}{2}\cdot\rho_{air,ACT}\cdot\dfrac{\pi}{4}\cdot D^{2}}} \quad (2)$$

where: $P_{air,IN}$ - aerodynamic power of the wind in front of the blades; $P_{air,OUT}$ - aerodynamic power of the wind measured at the anemometer; $\rho_{air,ACT}$ - air density at the height of WTs; calculated based on the standard air density of 1.225 kg/m^3 at the sea level; D - diameter of the blades; D_{OUT} - diameter of the stream tube at the anemometer location; P_{el}- electrical power output, η_{gear}; η_{DFIG} - gearbox and DFIG efficiencies; $s_{w,OUT}$- wind speed recorded by anemometer; and $s_{w,IN}$ – recalculated wind speed in front of the blades.



a)

b)

Fig 3. Measured power curves for wind speed corrected in front of the blades. a) WT4 from the UK site; b) WT15 from the Italian site.

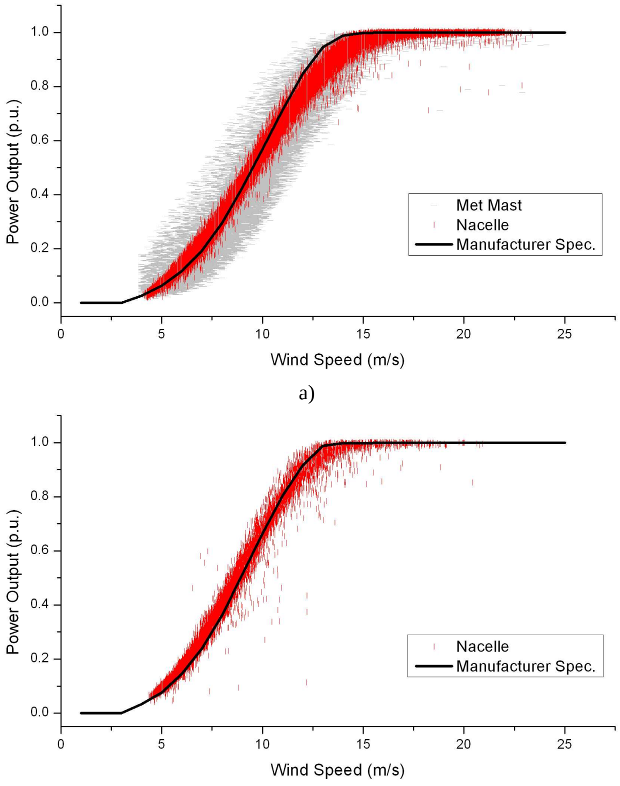
The changes in the results for measured power curves after the wind speed correction are illustrated in Fig.3, again for WT4 from UK wind farm and WT15 from Italian wind farm. It is clear that for the most of input wind speeds, the actual power outputs (represented by the measured power curves) are lower than those obtained using the manufacturer power curve. For example, the decrease in power outputs for higher wind speeds is due to the occurrence of short-duration cut-out wind speeds in the recorded average 10-min values.

C. Equivalent power curves of the whole wind farms

Using the basic principles outlined in the previous sections, equivalent power curve models of the two considered wind farms can be created using both AMPC and CMPC methods. As the equivalenting of the whole wind farm requires simultaneous measurements at all individual WTs, the recorded data are filtered, and entries without readings at all WTs are discarded. Additionally, data entries with unrealistically high or low power outputs, data influenced by system faults, measurement errors or availability issues are also removed from the data set. Afterwards, the aggregation process can be carried out in order to obtain the equivalent power curve models of the UK and Italian wind farms.

C.1. Equivalent AMPC wind farm models

Fig. 4 shows normalised scatter plots of the power outputs from the two wind farms (1 p.u. corresponds to the sum of the rated powers of all WTs in each wind farm) obtained after the recorded data has been filtered. These data are plotted against the normalised manufacturer power curves, where 1 pu corresponds to the rated power of the WT.



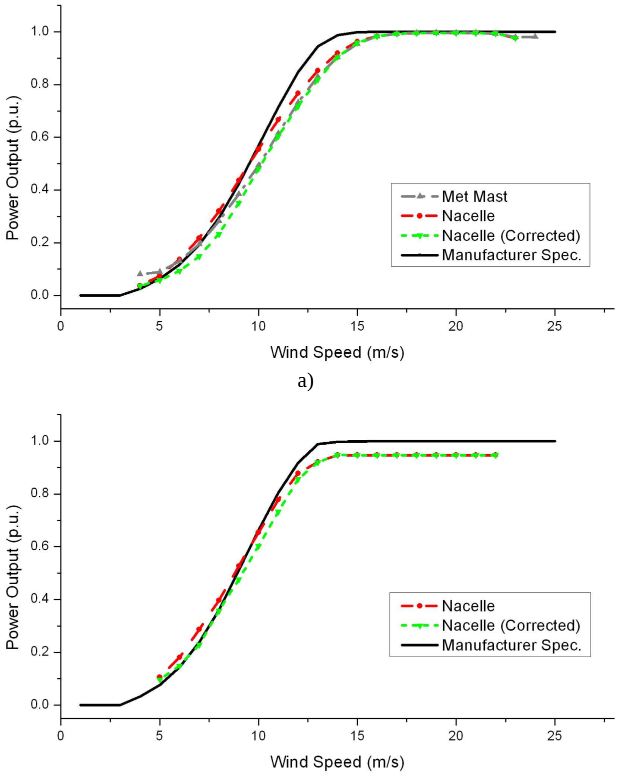
a)

b)

Fig 4. Normalised scatter plot of aggregate power outputs: a) UK wind farm; b) Italian wind farm.

In Fig. 4a (UK wind farm), the first set of data illustrates normalised aggregate power outputs as a function of the average values of nacelle-measured wind speeds at all individual WTs, whereas the second set of data plots normalised aggregate power outputs as a function of mast-measured wind speeds. Fig. 4b shows the corresponding results only for average nacelle-measured wind speeds, as there was no mast in the Italian wind farm.

The power outputs for the nacelle wind speeds in Fig. 4a are much less scattered than the corresponding mast-measured values. This is due to the fact that the nacelle measurements represent the normalised mean of all WTs, hence averaging effects remove some of the more outlying data points. The normalised aggregate-measured power curves (AMPCs), which can be used for equivalenting the whole wind farm, are then simply obtained using the "method of bins" (1), Fig. 5. The normalised power output may not reach unity for higher values of wind speed due to effect of averaging the power output across the whole site (Fig. 5b). This is the case when the site is located on very irregular terrain and the wind speed profiles vary significantly between WTs.



a)

b)

Fig. 5. AMPC equivalent wind farm model: a) UK site; b) Italian site.

C.2. Equivalent CMPC wind farm model

The application of the CMPC method for obtaining equivalent power curve model of a wind farm requires a different approach. Instead of having just one equivalent power curve model, the clustering algorithm can provide one or more equivalent power curves, as the number of equivalent curves generally depends on the input wind and output power patterns of individual WTs within the wind farm.

Fig. 6 illustrates a sample of the clustering results for the UK wind farm in a given time interval. This is the solution of two clusters with the wind speed corrected in front of the blades. This is the case in which the smallest error is achieved when the estimation of the energy output is performed. The first cluster contains WT 1 and 2, whereas the other four WTs are assigned to the second cluster.

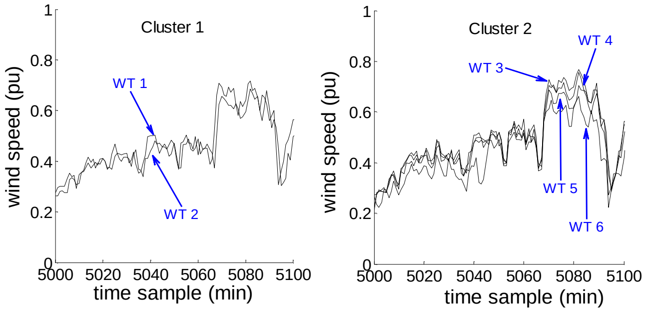
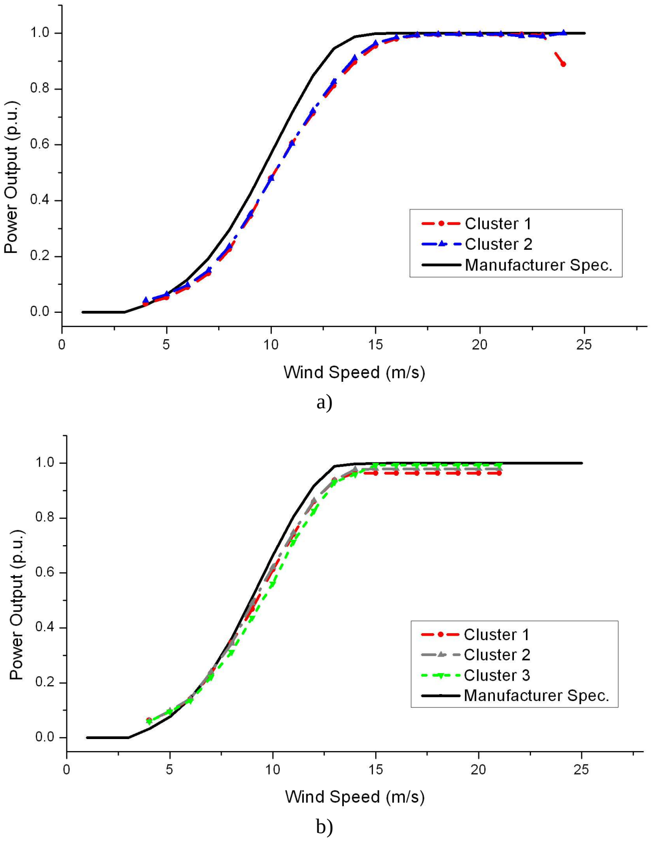


Fig 6. Clustering results for the UK wind farm, showing the solution with the smallest error in estimating the energy output.

Fig. 7a shows some of the results for equivalent power curves obtained using CMPC method for UK wind farm represented by two clusters, while Fig. 7b shows the corresponding results for Italian wind farm represented by three clusters and three corresponding equivalent power curves. In both cases, the corrected nacelle-measured wind speeds are used, and 1 p.u. corresponds to the sum of the rated powers of all WTs within each cluster. For the UK case, the difference between clusters is low, being the site located on the regular terrain. However, the CMPC provides more different clusters in the Italian case, due to the irregularity of the terrain.



a)

b)

Fig. 7. CMPC equivalent wind farm model: a) UK site; b) Italian site.

IV. APPLICATION OF EQUIVALENT POWER CURVE MODELS

The equivalent power curve wind farm models presented in the previous section can be used for steady state performance analysis in a variety of applications where the considered wind farm should be represented by a reduced equivalent model.

In this paper, the performance of the two proposed wind farm equivalenting methods (AMPC and CMPC) is assessed by comparing measured and estimated annual energy productions for both the UK and Italian wind farms.

A. *Estimated energy outputs of the UK wind farm*

The estimation of energy outputs using a power curve is a straightforward procedure, assuming that the curve itself and measurements of input wind speeds are both available. For a given set of input wind speed data, the active power outputs are determined from the power curve, and energy production is then estimated by considering the total period of time for which the specific outputs are available.

The results in Table I (second and third column) clearly show that the annual energy output of a single WT in UK wind farm (WT 4) are overestimated by around 10 % if the manufacturer power curve is used to calculate/estimate energy outputs. A more accurate estimation, with an error of less than 1%, is achieved when the measured power curve is used. The same conclusion can be drawn when the whole UK wind farm is modelled as an equivalent power curve with the AMPC method (fourth and fifth columns in Table I). The calculated annual energy outputs for three input wind speeds (at the nacelle, mast and for corrected nacelle measurements) are very close to the actual recorded values (all with less than a 1 % error), while an error of about 8 % is obtained when manufacturer power curve is used. The smallest error with the AMPC method is obtained when nacelle corrected wind speeds are used. These results clearly demonstrate that an equivalent steady state model of the wind farm can be established using the AMPC method.

TABLE I

AMPC METHOD: ESTIMATED ENERGY PRODUCTION FOR UK WIND FARM.

Calculation Method	**Individual: WT 4**		**Whole Wind Farm**	
	Energy (GWh)	**Error (%)**	**Energy (GWh)**	**Error (%)**
Actual Recordings	9.340	-	57.079	-
AMPC (Mast)	9.271	0.739	56.642	0.766
AMPC (Nacelle)	9.269	0.760	56.990	0.156
AMPC (Corrected)	9.341	0.011	57.066	0.023
Manufacturer Power Curve	10.237	9.604	61.424	7.612

The energy output is calculated by summing up the 10-minute energy values gathered from the actual recordings. If the wind speed values corresponding to the power output values were totally correct (i.e., representing the ideal information needed to build the power-wind speed curve), the total energy reconstructed by using these wind speed values would be exactly equal to the actual one. In this case, the AMPC method (that uses only averaging functions) would be able to provide the exact total energy. The mismatch in the total energy calculation depends on the fact that the wind speeds are not “ideal” for our purposes. This happens because the wind speed is measured either at the mast (i.e., in a different location with respect to the wind turbines) or at nacelle (thus being subject to the wind speed changes when wind passes through the blades). From Table I, the mismatch in these two cases is relatively low, but can be further reduced by correcting the wind speed as indicated in Section III.B.

The CMPC method for representing the whole wind farm with a different number of clusters produces results with similarly small errors (less than 1% in all cases, with one-cluster CMPC results matching the AMPC results), but the errors slightly increase as the number of clusters increases. This is perhaps surprising, as it would be expected that the error should decrease in the case of a more detailed model (i.e. model with more clusters). A simple explanation is that the energy production is overestimated by CMPC method when data measured at the nacelle of each individual WT are used.

The above results demonstrate the importance of the correction of the wind speeds measured at the nacelle (these results are marked as “corrected” in Table I and II), as the corresponding results for annual energy productions provide an almost exact match with the actual measurements.

TABLE II
CMPC METHOD: ESTIMATED ENERGY PRODUCTION FOR UK WIND FARM.

Calculation Method	**Cluster components**	**Energy (GWh)**	**Error (%)**
Actual Recordings	-	57.079	-
CMPC – 1 cluster	{1, 2, 3, 4, 5, 6}	56.990	0.16
CMPC – 1 cluster (corrected)	{1, 2, 3, 4, 5, 6}	57.066	0.022
CMPC – 2 clusters	{1, 2}, {3, 4, 5, 6}	56.934	0.250
CMPC – 2 clusters (corrected)*	{1, 2}, {3, 4, 5, 6}	57.069	0.017
CMPC – 2 clusters	{1, 2, 3}, {4, 5, 6}	56.895	0.320
CMPC – 2 clusters (corrected)	{1, 2, 3}, {4, 5, 6}	57.055	0.041
CMPC – 3 clusters	{1}, {2, 3, 5}, {4, 6}	56.843	0.410
CMPC – 3 clusters (corrected)	{1}, {2, 3, 5}, {4, 6}	57.064	0.027
CMPC – 6 clusters or detailed model	{1}, {2}, {3}, {4}, {5}, {6}	56.637	0.770
CMPC – 6 clusters (corrected) or detailed model	{1}, {2}, {3}, {4}, {5}, {6}	57.084	0.009

* best solution

B. *Estimated energy outputs of the Italian wind farm*

The analysis from the previous section is repeated for the 32-turbine Italian wind farm. However, available recorded data for individual WTs from the Italian wind farm have large series of inputs without simultaneous entries for all WTs. Although this suggested that the analysis of the Italian wind farm, which consists of three wind parks, should be performed for each wind park separately, this is not done in this paper due to the space limitation (these results will be given in a future publication). The results for the estimated energy productions with the AMPC methods for a single turbine from the Italian wind farm (WT 15) and for the whole wind farm are illustrated in Table III. As in the case of the UK wind farm, the errors are less than 1 % and the best matching is obtained for the corrected nacelle measurements, while use of manufacturer power curve gives 5-7 % errors.

TABLE III
AMPC METHOD: ESTIMATED ENERGY OUTPUTS FOR ITALIAN WIND FARM.

Calculation Method	**Individual: WT15**		**Whole Wind Farm**	
	Energy (MWh)	**Error (%)**	**Energy (MWh)**	**Error (%)**
Actual Recordings	262.310	-	771.911	-
AMPC (Nacelle)	261.786	0.199	769.205	0.351
AMPC (Corrected)	262.5542	0.093	770.881	0.133
Manufacturer Power Curve	276.2367	5.231	828.1545	7.286

The results of the CMPC method (Table IV), however, show that the accuracy (in some cases slightly greater than 1%) is influenced by a relatively small size of measured data set with all individual wind turbines. In other words, the CMPC method requires a larger set of input data for better representation of the whole wind farm with the equivalent power curve models.

TABLE IV
CMPC METHOD: ESTIMATED ENERGY OUTPUTS FOR ITALIAN WIND FARM.

Calculation Method	**WT cluster components**	**Energy (MWh)**	**Error (%)**
Actual Recordings	-	771.911	-
CMPC – 1 cluster	{1-32}	769.205	0.351
CMPC – 1 cluster* (corrected)	{1-32}	770.881	0.133
CMPC – 2 clusters	{1-13, 16-25, 27, 29-32}, {14, 15, 26, 28}	763.682	1.066
CMPC – 2 clusters (corrected)	{1-13, 16-25, 27, 29-32}, {14, 15, 26, 28}	769.650	0.293
CMPC – 3 clusters	{1-6, 13, 17, 19-25, 30, 32}, {10-12, 14-16, 26-29, 31}, {7-9, 18}	768.890	0.391
CMPC – 3 clusters (corrected)	{1-6, 13, 17, 19-25, 30, 32}, {10-12, 14-16, 26-29, 31}, {7-9, 18}	769.262	0.343
CMPC – 6 clusters	{6, 23}, {3, 16-22, 29-32}, {1, 2, 4, 5, 7-10, 12-14, 27}, {11, 26, 28}, {24, 25}, {15}	761.973	1.288
CMPC – 6 clusters (corrected)	{6, 23}, {3, 16-22, 29-32}, {1, 2, 4, 5, 7-10, 12-14, 27}, {11, 26, 28}, {24, 25}, {15}	773.896	0.257

* best solution

C. *Discussion of the results*

Comparison of the results of the two proposed methods for equivalenting wind farms (AMPC and CMPC, with or without the correction of nacelle-measured wind speeds) shows that both proposed methods provide a very good matching with the measured annual energy outputs (errors are less than or around 1 %), which is significantly better than the results produced using the manufacturer power curve (up to 10 % error). If the nacelle-measured wind speed values are corrected (i.e. if the actual wind speeds in front of the WT blades are calculated), this will provide almost exact matching with the measurements. After the correction of the nacelle-measured wind speeds, the CMPC method is generally more accurate than the AMPC method. However, the CMPC method may require more than one equivalent power curve to represent the whole wind farm, whereas the AMPC approach requires only one equivalent power curve. The error in the estimation of the energy outputs of a wind farm modelled with a single equivalent machine (i.e. with a single equivalent power curve) may be higher for bigger wind farms with a larger number of WTs, although the results for the Italian wind farm do not demonstrate that. Larger wind farms will also require more measurements and recordings in order to be accurately modelled with the CMPC method, as it is demonstrated in the example of Italian wind farm.

V. CONCLUSIONS AND FURTHER WORK

Two methods for obtaining equivalent power curve models of a wind farm based on the field measurements have been proposed in this paper. Both methods and resulting models are specifically intended for the assessment of the wind farm steady state performance. The first method, denoted in this paper as the “aggregate-measured power curve” (AMPC) method, provides a single equivalent power curve model of the wind farm by averaging recorded input wind speeds and output powers for all WTs in the wind farm. The second proposed method, denoted here as the “cluster-measured power curve” (CMPC) method, applies the SVC algorithm to the measured data in order to identify distinctive clusters/groups of the WTs, which are then represented with the corresponding equivalent power curves. In this way, the CMPC method may produce more than one equivalent power curve model. The effectiveness of both methods is demonstrated and validated by a direct comparison of estimated annual energy productions with the measured results for two wind farms (with very different characteristics).

The results of the work presented in this paper show that both methods for equivalenting wind farms with a simple power curve model allow for an accurate and quick estimation of energy production. Essentially, the proposed models can be used instead of a more detailed wind farm representation, relying on a higher number of equivalent machines.

Further work and research will be aimed at investigating other possible applications of the proposed equivalent power curve wind farm models (besides the estimation of energy outputs), where appropriate modelling of dynamic characteristics and performance of both individual wind turbines and overall wind farm is of particular interest.

VI. ACKNOWLEDGEMENT

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