ECO 122 wind turbine extensive validation with field data

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SUMMARY

The aim of the paper is to present the validation of the ECO 122 design through dynamic and performance measurements done on the ECO 122 2.7 MW prototype. The ECO 122 design is done on the basis of optimising efficiency and with the objective of obtaining a reliable wind turbine product. This design is developed using a specific methodology that depends on the standards and the know-how of the company and through numerical models commonly used for the dynamic characterization and performance prediction of wind turbines. Nevertheless such methodology, code and models need to be validated against field measurements, comparing the theoretical and real results in terms of wind turbine dynamics and performance. The final conclusion of the analysis is the extensive validation of the ECO 122 2.7 MW product, filling the basis for the upgrade to the new 3.0 MW rated power.

1. INTRODUCTION

The ECO 122 2.7 MW is a new generation of onshore wind turbine with large rotor diameter. The unit installed at ECN site (Holland) operates at its nominal power of 2.7 MW and data collected are used to validate this new wind turbine model. All final testing prior to obtain Type certificate have been finished, exceeding certification bodies' requests in order to extensively check its dynamics, performance and reliability. In this way extra sensors not strictly needed for the certification (e.g. blade, nacelle and tower accelerometers) are added to the wind turbine to provide the necessary data to do an extensive analysis.

For the dynamic characterization and validation, experimental modal analysis is a good way to check the wind turbine modal behaviour predicted by the models. However, the application of conventional experimental modal analysis techniques is not feasible due to the wind turbine size and Operational Modal Analysis (OMA) is the best choice to do dynamic validation. Such modern modal analysis technique allows estimating the modal parameters based only on the measured responses of the system under operation, i.e. without artificial excitations.

Concerning the performance validation, statistical analysis of all the data collected during the measurements campaign is done to make sure that the loads are within the expected levels. Individual equivalent loads calculation for each time series and rainflow analysis with all the database are also done to check the fatigue of the wind turbine. Finally power measurements made while loads are measured are used to prove that the energy produced by ECO 122 wind turbine is in line with the predictions.

Although the wind turbine characteristics are analysed considering all the reference systems with similar results, the data shown is reduced to the rotor to make this document more synthetic and to focus the analysis on the only component with completely new design: the wind turbine blade.

2. INSTRUMENTATION AND AEROELASTIC MODEL DESCRIPTION

2.1 Instrumentation

New wind turbine prototypes must be instrumented with a set of sensors to carry out the certification measurements required to get the approval to commercialize the new product. All these measurements as well as the instrumentation required are specified in IEC 61400-13. But, in order to validate the electrical, dynamic and load performance and to get a thorough experimental characterization of the turbine, ECO122 2.7 MW prototype has been instrumented with extra sensors not specified in the standards. All this instrumentation gives key information to validate and update the numerical models used by the design areas. As this paper is mainly focused in the dynamics and performance validation of the wind turbine, only the instrumentation used for that purpose is described. It can be split into rotating and non-rotating reference frames.

The rotating reference frame instrumentation is composed by two accelerometers installed on each blade at 28 meters from blade root measuring both Edgewise and Flapwise accelerations and strain gauges located at blade root to measure Edgewise and Flapwise bending moments. All the accelerometers installed in this wind turbine are MEM’s DC response accelerometers in order to measure the very-low excitation and natural frequencies of the lower order modes.

The non-rotating reference frame is instrumented with triaxial accelerometers on the rear part of the rear frame, on the central frame (region located immediately above the tower) and on the front frame. Tower top and tower intermediate accelerations and bending moments are also measured using accelerometers and strain gauges. Finally tower base bending moments are measured with strain gauges.

2.2 Aeroelastic model

In order to estimate ECO122 2.7 MW characteristics in terms of dynamics and loads aeroelastic simulations are performed with GH Bladed software, the same software that has also been used for the certification of the turbine. The simulation model is exactly the same than the one used to do the simulations for certifications purposes except from the foundations characteristics that are adapted to the ECN site ones. GH Bladed is industry standard software, developed by independent consultant Garrad Hassan and validated by Germanischer Lloyd, for the design and certification of onshore and offshore wind turbines.

3. WIND TURBINE DYNAMICS VALIDATION

For the certification and validation of ECO 122 2.7 MW wind turbine around 4000 10-minutes time series covering its entire operating conditions were recorded. This measurement campaign was done by ECN accredited body from December 2013 to March 2014 and through the sensing conducted in the prototype which was described in previous section. As stated in the introduction, although the wind turbine dynamics are analysed in terms of all the natural modes and frequencies with similar results, the data shown is reduced to the rotor.

Operational Modal Analysis (OMA) is the chosen method to perform the dynamic validation (see [1]). OMA methodology is based on the singular value decomposition (SVD) of the power spectral density matrix. The singular values can be represented as a modal indication function (MIF) curve, where each peak indicates the existence of a mode. Furthermore, OMA uses an optimization method (Polyreference Least Square Complex Frequency method) to find the natural frequencies, dampings and mode shapes of a theoretical model that better represents the measured power spectral density matrix. This optimization is carried out for different orders of the model to improve the mode identification. The modes resulting of this optimization method are represented together with the MIF curve in the stabilization diagram. The natural frequencies are then extracted by evaluating this stabilization diagram (see Figure 1).

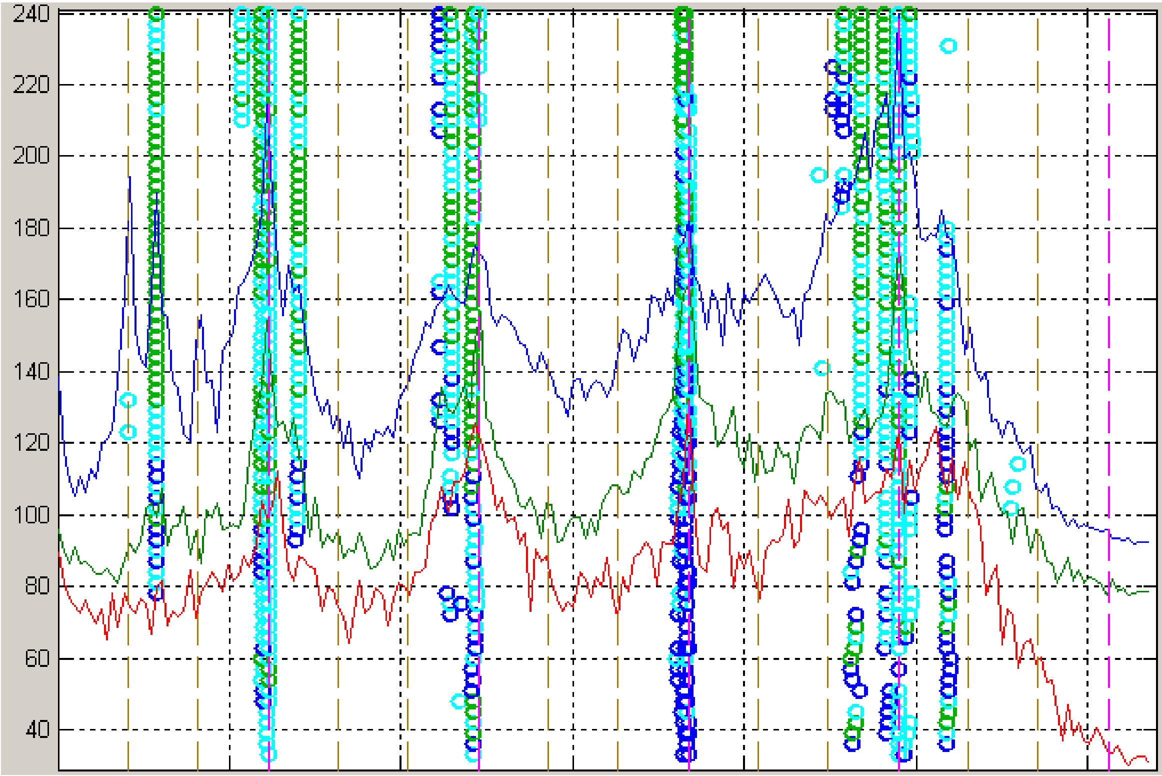


Figure 1: Example of stabilization diagram obtained as a result from OMA method.

3.1 Experimental modal parameters of ECO122 2.7 MW in operating conditions

Before starting the analysis it must be stated that the high damping of Flapwise modes makes difficult its identification. In the case of Edgewise eigenfrequencies they can be clearly identified through the analysis of blade acceleration along Y axis due to a change in the vibration activity at these specific frequencies with respect to the others. On the other hand for blade X acceleration the activity is blurred with only marked acceleration near excitation frequencies (P's harmonics), making difficult Flapwise eigenmodes identification. In the following sections only clearly identified eigenmodes are plotted and compared with values obtained from numerical models. This analysis is currently under development and is only done for low wind speed values. It will be completed for the whole wind turbine operational range in the near future.

3.1.1 Rotating reference frame

Rotor natural frequencies of lower order modes in the rotating reference frame are presented in Waterfall diagram form. The results of OMA performed with experimental data are plotted as diamonds, whilst the aeroelastic model results are plotted as continuous lines. Note that the colour used to represent each mode is the same in both cases.

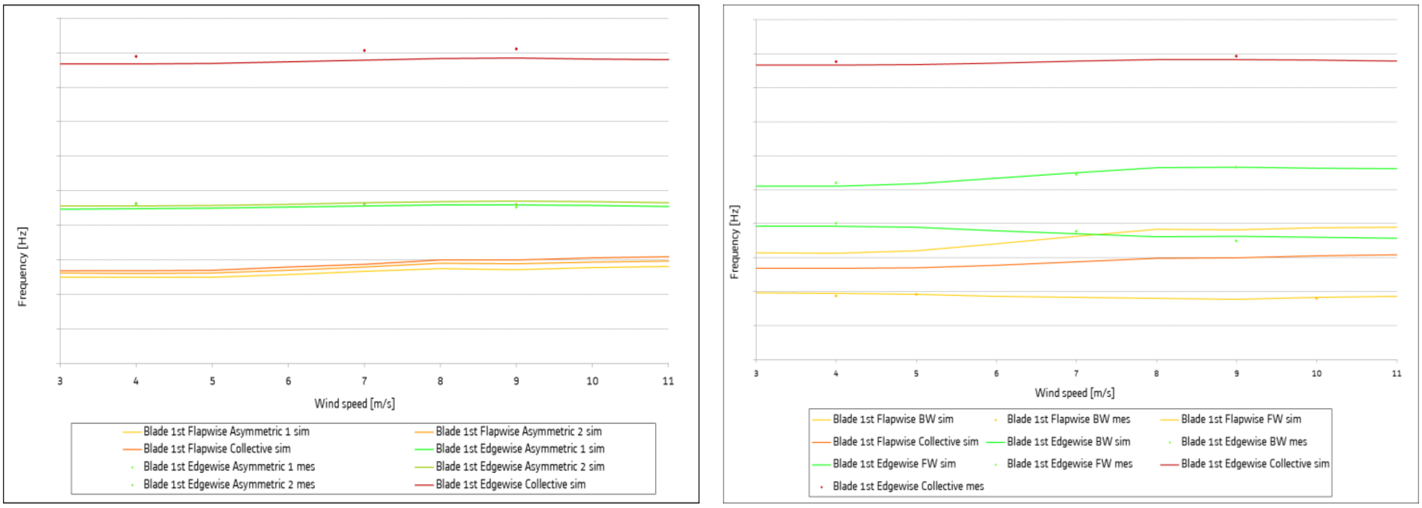


Figure 2: Waterfall diagram in rotating and non rotating reference system respectively.

As it can be observed on Figure 2 left plot, the natural frequencies obtained with OMA match well with those predicted by the aeroelastic model. Indeed, the relative error is smaller than 3.2% for all the analysed modes, thus it assures that the structural integrity of the turbine is not jeopardized. Further analysis is being carried out to improve the identification of Flapwise modes and to complete the current results to cover the whole wind speeds range.

3.1.2 Non rotating reference frame

Figure 2 right plot shows a Waterfall diagram with the lower order rotor natural frequencies but in the non-rotating reference frame. The dependence of the Backward and Forward Whirling modes is clearly visible in the region of variable rotor speed (between 5 and 8 m/s). Again, the relative error between aeroelastic model and OMA estimates is reduced (less than 3.6%), which means that the structural integrity of the turbine is not compromised.

4. PERFORMANCE VALIDATION

In the same way as is done for the dynamics analysis the loads comparison will be focused on blade component. The data shown in the following sections represents a capture matrix containing more than 500 measurements of 10-minutes timeseries which is a representative result of the measurement campaign carried out on the ECO 122 2.7 MW prototype by ECN accredited body during 3 months. All these measurements are done using the sensors quoted in the previous pages. Comparisons between the measurements and the values obtained with simulation model and following the IEC 61400-1 standard are shown in the following sections. In order to get the most reliable analysis possible, site specific conditions in terms of turbulence intensity, air density, wind shear and inflow angle have been applied on simulations in order to perform a proper comparison with measurements. The performance validation is finalized with a comparison between the certified and the predicted power curves.

4.1 Loads statistical analysis

The statistical analysis consists in plotting the maximum, mean and minimum values of the variables for each 10-minute time series of power production data, as well as simulated data in site conditions. The results obtained for blade root strain gauges in both Y and X axes are shown in Figure 3.

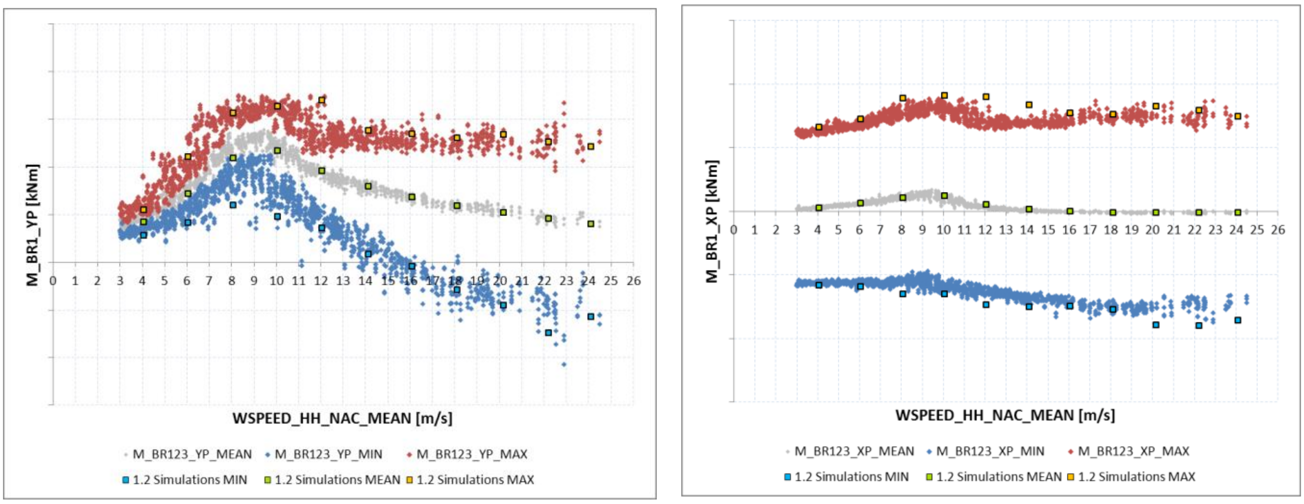


Figure 3: Statistical analysis result for blade root M_y and M_x bending moments.

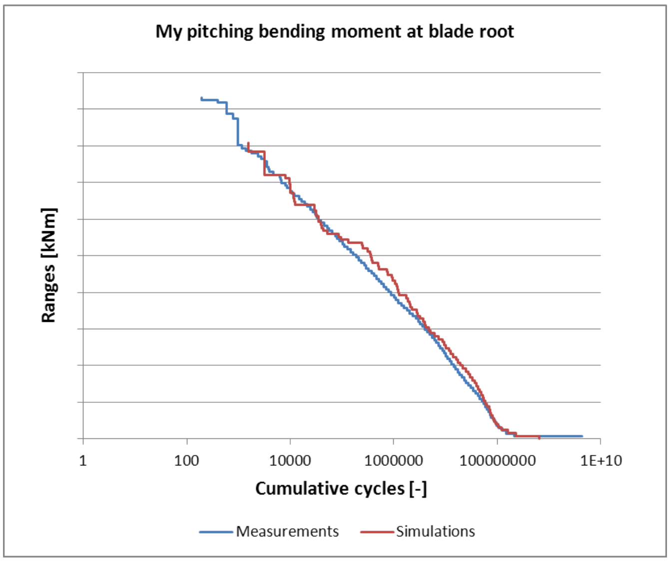
In the graphics maximum, mean and minimum values are shown as red, grey and blue points respectively. The results of the simulations done with numerical model with a step of 2 m/s are superimposed to these measured values. Good agreement is found between the measurements done on the prototype and the loads obtained from the simulations in terms of statistical loads comparison. The simulated points follow the tendency shown by the measurements which indicates that the numerical model is representative of the real one. Moreover not much dispersion of the values is observed, showing a good stability of the loads in the wide range of external conditions suffered during the measurements campaign in terms of turbulence intensity, air density, wind shear and inflow angle which demonstrates the robustness of the design.

4.2 Fatigue loads analysis

For the fatigue loads verification rainflow counting algorithm is applied to the entire database of different stress time histories measured in the prototype and used in previous pages. With this output two types of analysis are done in this section: rainflow cycle distribution analysis and individual equivalent loads calculation. The results of the measurements are compared with the values obtained from the numerical models to check if the fatigue of ECO 122 2.7 MW is in line with the predictions used in its design.

4.2.1 Rainflow cycle distribution comparison

The analysis done in this section as a first step consists in obtaining a comparison of the cycle range distribution from measurements and numerical model predictions because it affects directly to the fatigue damage suffered by the wind turbine along its whole lifetime. In order to ensure the correct weighting balance of each measured timeserie a probability of occurrence during whole wind turbine life has to be applied on measurement. In the following analysis the rainflow cycle exceedance is evaluated for the ECO 122 2.7 MW design conditions: an extrapolated wind turbine lifetime of 20 years and with a Class III (7.5 m/s average wind speed) Weibull distribution. This process gives an output which represents the whole wind turbine life. The rainflow cycle counting final output can be presented in different formats and rainflow cycle by exceedance is used here because it allows comparing the cycle distribution in a visual way making easier the comparison between measurements and calculations. In this type of analysis the mean values of the cycles are not taken into account but these mean values are checked in the statistical analysis done in the previous section. The results obtained for blade root strain gauges in both Y and X axes are shown in Figure 4.



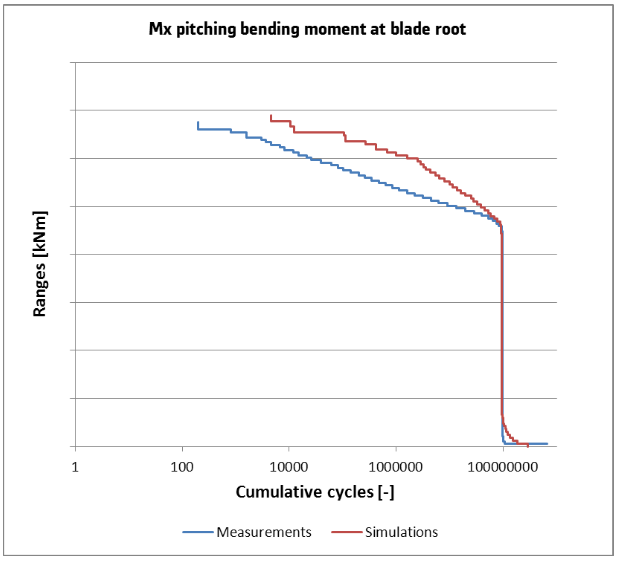


Figure 4: Rainflow cycle distribution comparison for blade root M_y and M_x bending moments.

In the graphic rainflow cycle exceedance obtained from the measurements is represented with a blue line and the values from the simulations are plotted as a red line. Concerning the bending moment around Y axis very good correlation is found between measured and simulated data in the entire ranges domain. On the other hand, for the bending moment around X axis, results are very comparable for higher accumulated number of cycles and conservative with respect to the measurements in the lower domain. The final conclusion obtained from the rainflow cycle counting analysis is that good agreement or slightly conservative approach is found between the measurements done on the prototype and the loads obtained from simulations.

4.2.2 Equivalent loads comparison

In order to complete the fatigue comparison started in previous section with a deeper analysis, equivalent loads comparison between the individual values obtained from each measurement and the calculations done with numerical models is also done here. Before starting this analysis it will be necessary to define the inverse slopes for each component material and consequently for each coordinate system which, in the case of the blade, leads to m=10 and the equivalent loads obtained for this slope will be shown here. The results obtained for blade root strain gauges in both Y and X axes are shown in Figure 5.

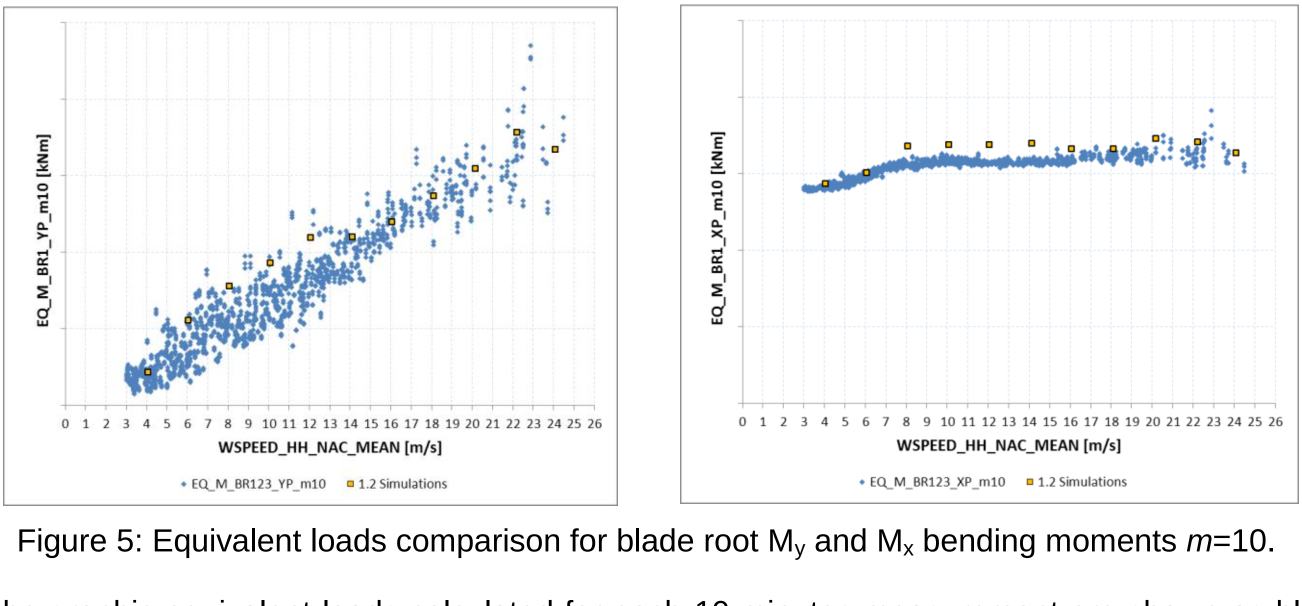


Figure 5: Equivalent loads comparison for blade root M_y and M_x bending moments m=10.

In the graphic equivalent loads calculated for each 10-minutes measurement are shown as blue points. Also the results of the simulations done with numerical model with a step of 2 m/s are superimposed to these measured values. The final conclusion of equivalent loads analysis is that good agreement is found between the measurements done on the prototype and the loads obtained from the simulations. The obtained loads are in line or slightly over the predictions from simulations which shows that the numerical model is realistic or conservative in some cases. It must be also stated that in this specific analysis all the individual equivalent loads are shown without weighting the timeseries with the probability of occurrence as is done in the rainflow analysis shown in the previous section. It means that the displayed data covers all the wide site conditions variability in terms of turbulence intensity, air density, wind shear, etc. and the conclusion is that this variability is also covered by the simulations done with representative values as is done during the design.

Considering the results of the rainflow cycle counting distribution and the equivalent loads analysis it can be concluded that the results are in line or slightly conservative with respect to the predictions from numerical models, which reinforces the reliability and the robustness of the design similarly to the results obtained in the statistical analysis.

4.3 Power curve analysis

The ECO 122 2.7 MW Power Curve measurement is done by ECN accredited body following the IEC 61400-12 standard using a capture matrix data of more than 1700 10-minutes measurements, which are plotted in the following graph represented by blue points. These measured data is also binned with a wind speed step of 0.5 m/s and the obtained values are shown in red. Finally all these information is compared with the predicted power curve represented in green, which is adjusted to the site conditions in terms of air density and turbulence intensity. The result of all this process is shown in Figure 6.

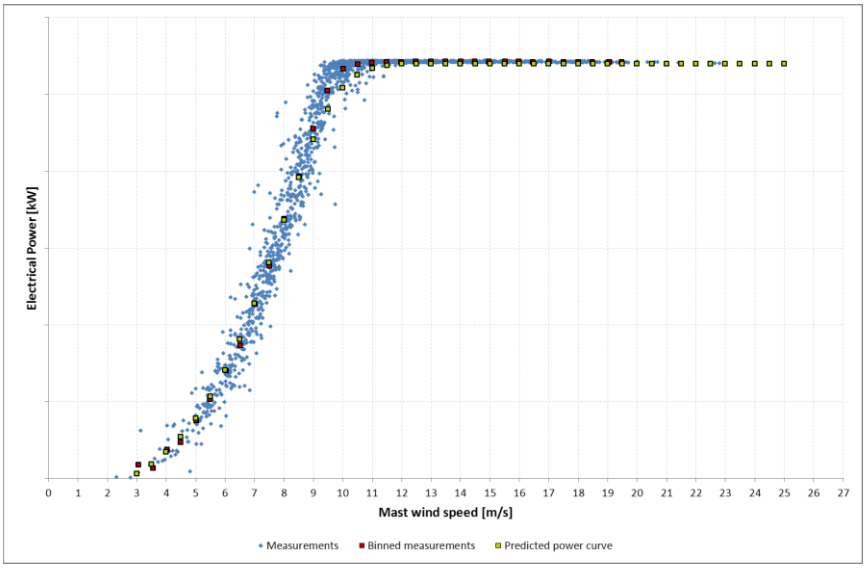


Figure 6: Power curve analysis results.

The results show good agreement between measured and predicted power curve in general. In the only wind speed range where a considerable discrepancy can be observed, near rated power, the measured power curve is exceeding the predictions and generated power values over the simulations are obtained. In order to try to better understand the results shown and make a proper balance between all wind speeds depending on the probability of each one an Annual Energy Yield calculation is done weighting both measured and predicted power curves with Weibull probability distributions and for different mean wind speed values. It makes possible to check ECO122 2.7 MW performance in all the different site conditions where it will be installed. The results show that more than 100% of the predicted annual energy production is obtained from the low wind speed (6 m/s) to the high wind speed (10 m/s) values used in the calculation. This fact added to all the analysis done in this section shows that ECO 122 2.7 MW is a highly reliable product with a strongly proved performance.

4. CONCLUSIONS

The extensive experimental measurement campaign carried out on the Alstom's ECO 122 2.7 MW prototype not only with the objective of its certification but exceeding standards requirements is used to do the validation proposed on this paper. As a result, the modal characteristics of the global structure of the turbine under various operating conditions are available. Also loads have been measured and processed to monitor ECO122 prototype statistical and fatigue loads level. In parallel to the loads, power curve has also been measured to verify the energy capture obtained by the wind turbine. All these experimental values have been correlated with the numerical models, providing valuable information in the objective of ECO 122 2.7 MW design validation. The final conclusion is that the analysis done on the ECO 122 2.7 MW prototype proves that it is a reliable and efficient product, demonstrating its robustness and optimisation. This fact fills the basis for the upgrade to the new 3.0 MW rated power.

REFERENCES

[1] D. Tcherniak, S. Chauhan and M.H. Hansen, Applicability Limits of Operational Modal Analysis to Operational Wind Turbines, *Proceedings of the IMAC-XXVIII*, Jacksonville, Florida, USA, 1–4 February, (2010).